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Abrasion Damage of Textile Fibers*

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Abstract

The inherent abrasion behavior of 14 different textile materials in the form of yarns was investigated. Abrasion was expressed by the abrasion damage, which is the opposite of abrasion resistance. Abrasion damage was measured quantitatively by the fiber fineness (grex) destroyed in flexing around a steel bar under standardized conditions using the Stoll-Quartermaster abrasion tester. The abrasion damages were evaluated relative to that of high-tenacity nylon multifilaments. Great differences exist in the abrasion behavior of various textile fibers. The damage of multifilaments increases from nylon to Dacron polyester fiber, viscose, Fortisan, Orlon acrylic fiber, Saran, silk, acetate, and casein, while that of staple yarns increases from nylon to Dacron polyester fiber, cotton, Fibravyl, Dynel, Kuralon, Thermovyl, wool, Orlon acrylic fiber, viscose, and acetate. Staple yarns were always more abraded than corresponding multifilaments. Although high elastic energy of fibers is the main factor preventing inherent abrasion damage, extensibility, yarn surface, and friction must also be taken into account in interpreting the abrasion behavior of various textile fibers.

Introduction

When textiles in contact with solid bodies are moved relative to each other, rubbing-off or abrasion occurs. The abrading substance can be another textile or materials such as metals, glass, leather, plastics, dirt, and grit. The abrasion is a result of deformations due to compression, tension, bending, shear, and also of cutting. These and other factors cause the gradual damage of textiles in service. It is known that abrasion is a major contributing factor to wear. Kaswell emphasized recently that a clear distinction should be made between abrasion and wear [6].

For any critical judgment of the potentialities of textile materials, quantitative data on their abrasion behavior is as necessary as data on their tenacity, extensibility, elastic recovery, etc. The majority of abrasion tests of textiles have been carried out on fabrics, and they reflect only in part the abrasive behavior of the fiber material itself, since the attrition is markedly influenced here by the fabric weave, texture, and finish. Although the abrasion of yarns is also affected by form factors (yarn size, structure, twist), their influence can be reduced greatly if differences in the samples tested are kept within reasonable limits. Tests performed on multifilamentous yarns with low twist reflect mainly the abrasion of the material itself. In staple yarns, however, the yarn structure and surface affect the abrasive behavior. The yarns selected for testing were without special finishes and, considering multifilamentous and staple yarns as separate groups, they did not differ greatly in form factors.

Not much is known about the inherent abrasive behavior of textile fibers [6]. According to Backer [3], abrasion resistance decreases from nylon to cotton, wool, viscose, acetate, and casein. This rather qualitative estimation is based on the results of numerous authors obtained between 1932 and 1948 using different types of testers and widely varied fabric and yarn samples. Ray [9] obtained a similar ranking from flex abrasion tests performed on wet fabrics using the Stoll-Quartermaster tester. In these tests, nylon was found to have the highest abrasion resistance, followed by Dacron, Orlon, wool, and cotton, while viscose and acetate had the lowest resistance. Comparable quantitative data on the abrasion of different yarns were also published by Matthes and Keworkian [7, 8], Hamburger [4], and Hicks and Scroggie [5]. Using the Taber tester, Hicks and Scroggie performed tests on yarns as well as on plain-weave fabrics, and they found that

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the "abrasion life" diminished from nylon to polyacrylonitrile, viscose, and acetate approximately in the ratio 1,000:237:165:83.

The abrasion of textiles can be measured quantitatively by the progressively diminishing thickness, by loss of weight, strength, and energy absorption, and by the number (or time) of reciprocating actions (cycles) to cause a partial or total failure. Cycle numbers at break is a convenient and frequently used method of expressing the results of laboratory abrasion tests, but it is by no means the best method. Such cycle numbers indicate the abrasion life of a material and they can be compared for different fibers. It is known, however, that they are greatly influenced by many details in the testing procedure. They can be evaluated quantitatively only if obtained on the same tester under identical conditions using comparable samples.

The purpose of this study is to investigate quantitatively the abrasive behavior of various textile materials. The abrasion of yarns is compared first on the basis of cycle numbers at break. An attempt is then made to measure the inherent abrasive damage of textile fibers by the yarn grex destroyed. Abrasion damage is a characteristic opposite to that of abrasion resistance, and it expresses the amount of substance rubbed off during the test performed. Finally, the abrasion damage of various textile fibers in the form of multifilamentous and staple yarns is measured and discussed.

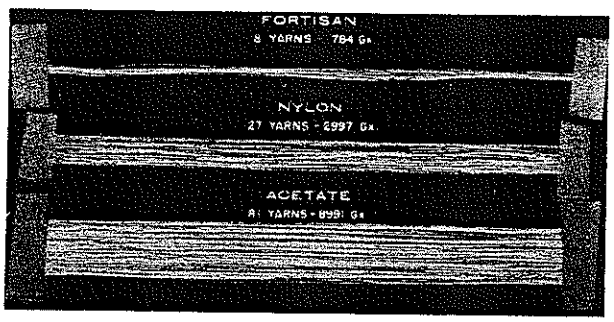

FIG. 1. *Yarn bundles.*

Yarn Abrasion

Yarn abrasion can be investigated in testers specially designed for fibers in which mostly single

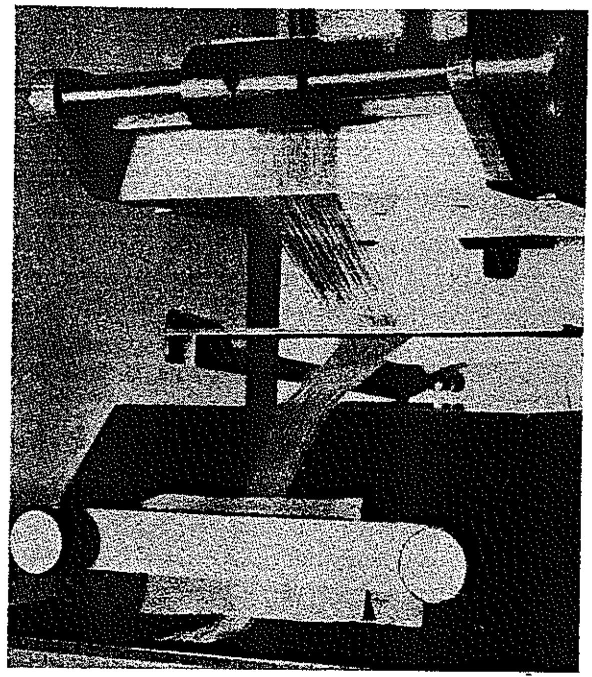

FIG. 2. *Insertion of the yarn bundle into the Stoll-Quartermaster tester.*

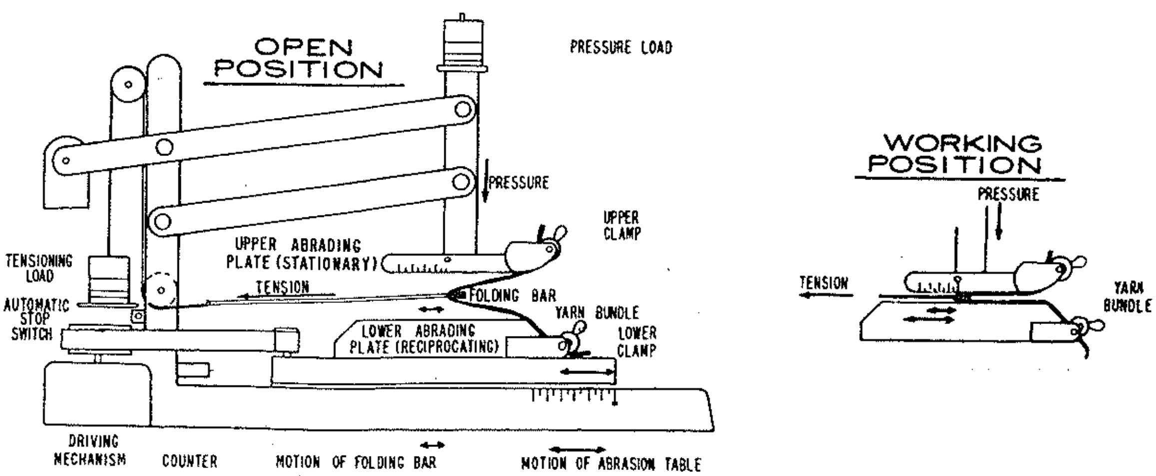

FIG. 3. *Yarn abrasion on the Stoll-Quartermaster tester.*

yarn strands are abraded. The models developed by Boehringer, Ecker, Jansen, Mecheels, Matthes (T. H. Aachen tester), Neumann, Oestermann, Weltzien, Zart [7, 8, 10, 16, 18], and Walker and Olmstead [17] represent such testers. The abrasion of yarns can be also measured quantitatively in fabric abrasion testers, in which a correlation between yarn and fabric abrasion tests is easily obtained. Such a correlation is frequently needed, either when yarns with known abrasion serve for the construction of fabrics or when abrasion tests performed on fabrics must be rechecked and interpreted by the abrasion of warp and filling yarns removed from the fabric.

The fabric abrasion testers of Schiefer, Stoll, Taber, and Wyzenbeek are the models most used in this country at present [1, 2]. In the Schiefer tester [1, 11], a circular plastic clamp is provided permitting 54 portions of the same yarn strand to be abraded simultaneously. In the Taber [5] and Stoll-Quartermaster [12, 13] testers, the fabric sample must be replaced by an assembly of parallel yarns suitably inserted in the tester. The Taber tester measures the flat abrasion of yarns against steel either parallel or perpendicular to the fiber length. Such tests were carried out by Hamburger [4] and by Hicks and Scroggie [5].

Flex Abrasion Using the Stoll-Quartermaster Tester

The tests reported in this study were performed on yarn bundles by flex abrasion using the Stoll-Quartermaster tester. The yarns were laid parallel in any desired number by a yarn reel. They were cut in sections of approximately 6 in. (15 cm.) in length, and were held together by masking tape placed on the ends, as shown in Figure 1. These two ends were clamped into the sample holders on the upper (stationary) and lower (reciprocating) abrasion plates of the tester, as shown in Figures 2 and 3. The yarn bundle itself was folded along a square-edged hardened steel bar of 2 mm. thickness (Figure 4) and inserted under tension in the tester (Figure 5). In addition, it was kept under the pressure of the abrasion head. Tension and pressure exerted on the yarns were controlled, and they were varied between 0.5 and 4.5 lbs. (227–2,041 g.) to increase or reduce the severity of the attrition. A constant stroke length of 0.5 in. (1.27 cm.), measured on the folding bar, and a constant stroke speed of 120 cycles (double strokes) per minute were maintained during all the tests performed.

Abrasion of the yarns by rubbing and flexing took place in the tester as a result of the forward and backward motion of the folding bar. The two rather sharp edges of the bar were perpendicular to the yarn length, and they caused the main attrition of the yarn bundle. The lines of highest abrasion moved up and down along the yarn bundle length during each cycle.

Figure 6 demonstrates schematically the position of the yarn bundle and folding bar during various stages of a flex cycle. The most severe attrition occurs on that part of the bundle which is bent and pressed four times around the edges of the folding bar during a full cycle (*i.e.*, around each edge, once in the forward motion and again in the backward motion). In Figure 6 this part is cross-hatched between numbers 3 and 6 in *B* and *C*, and it is shown greatly diminished in *D*. A minor flex abrasion takes place on the neighboring parts (between numbers 2 and 3, and also between 6 and 7) which passes the edges only twice (*i.e.*, passes one edge in the forward and backward motion). The flat abrasion of the yarn bundle by rubbing (between the horizontal surface of the folding bar and the upper or lower plate of the tester, respectively) can be neglected, because it is essentially less severe than the

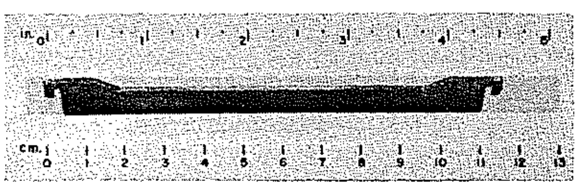

FIG. 4. *Folding bar.*

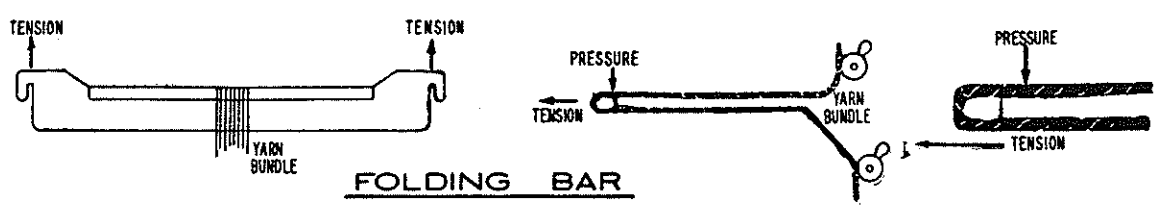

FIG. 5. *Position of the yarn bundle.*

abrasion by flexing around the edges of the steel bar. The yarn bundle breaks, of course, on that part where the most severe attrition takes place (Figure 6*D*).

Figure 7 demonstrates the progressive attrition of Fortisan, nylon, and acetate multifilament bundles after one-tenth, one-half, three-quarters, and all of the cycles necessary for their rupture. A permanent deformation (crimp along the folding bar) appears even at the beginning, and rupture of yarns occurs mainly at the end of the flexing procedure. After the rupture of a few yarns, the attrition proceeds very rapidly as a result of the increased tension to which the remaining yarns are subjected.* Rupture stops the reciprocating motion automatically, clearly indicating the end-point of total breakdown. All the cycle numbers reported in this study represent mean values of five tests performed under standardized atmospheric conditions, at 70°F (21.1°C) and 65% R.H. Consecutive tests were made by the same operator using the same tester and the same folding bar, and they were repeated frequently. This was considered important in view of the fact that reproducibility is a major problem in abrasion tests.

* This is discussed in more detail later (p. 217).

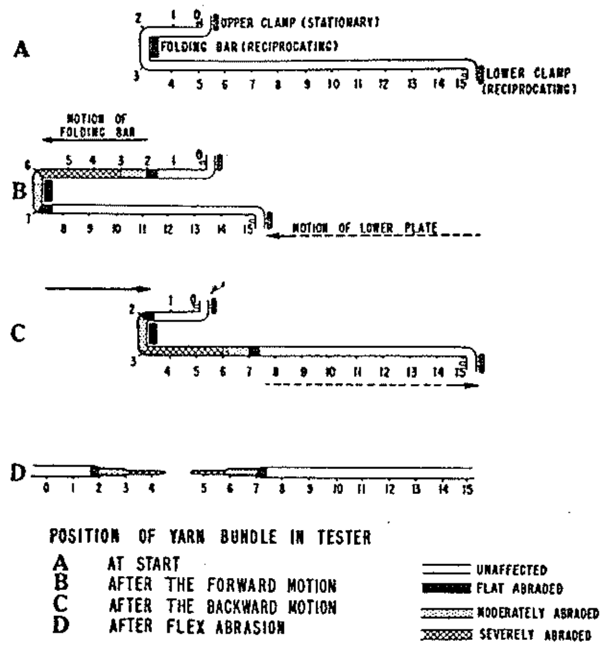

Fig. 6. *Schematic demonstration of a flex cycle.*

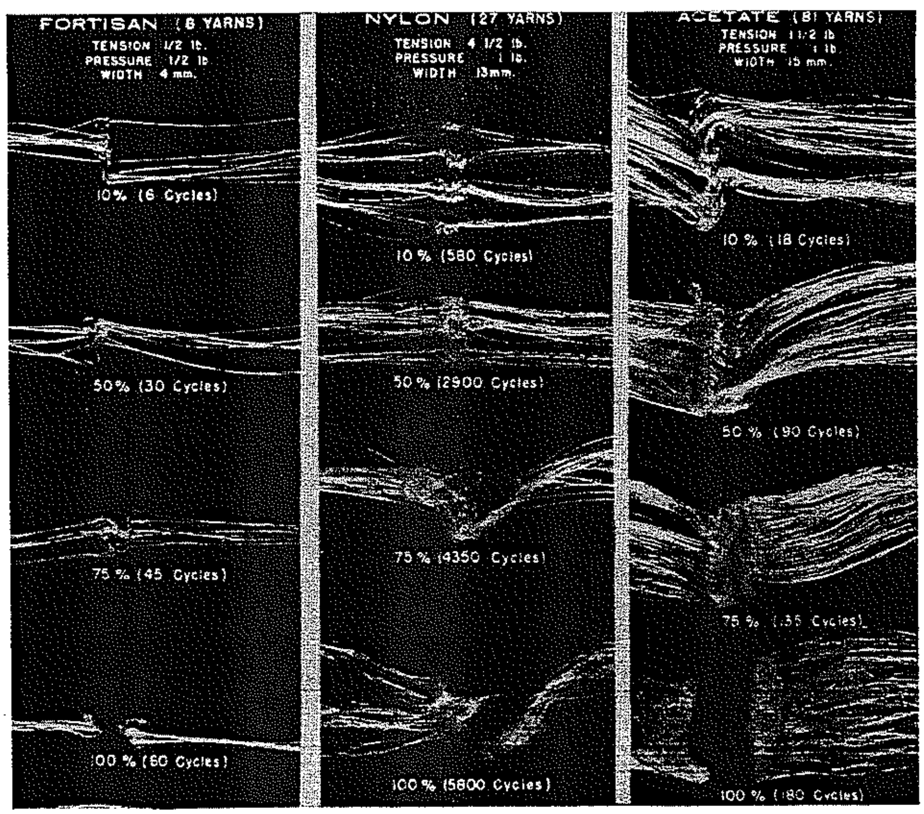

Fig. 7. *Progressive attrition of yarn bundles.*

TABLE I. FLEX ABRASION OF NYLON AND ACETATE UNDER IDENTICAL CONDITIONS *

	Nylon multifilament 100/40/2.5	Acetate multifilament 100/40/2.5	
Yarn fineness	111 gx.	111 gx.	
Tenacity at break	5.45 g./gx.	1.25 g./gx.	
Elongation at break	21.4%	24.3%	
Number of yarn strands in the bundle	27	27	108
Over-all fineness of the yarn bundle (total grex)	2,997 gx.	2,997 gx.	11,988 gx.
Actual tension	0.68 g./gx.	0.68 g./gx.	0.17 g./gx.
Relative tension	13% of ultimate	55% of ultimate	14% of ultimate
Cycle numbers at break	6,199	2	19
Relative cycle numbers	1,000	0.3	3.3
Time of abrasion in a single test	51 min. 35 sec.	1 sec.	10 sec.

* Test conditions: Stoll-Quartermaster tester; square-edged steel bar; 120 double strokes per minute; stroke length (bar), 0.5 in. (1.27 cm.); tensioning load, 4.5 lbs. (2,041 g.); pressure, 1.0 lb. (454 g.); 70°F (21.2°C); 65% R.H.

Influence of Yarn Pressure, Tension, and Bundle Size (Grex)

Yarn bundles consisting of nylon and acetate multifilaments with the same form factors were first abraded under identical testing conditions, as shown in Table I. The two fibers represent extremes with respect to abrasion behavior, since nylon multifilaments have the highest abrasion-resistance of the known textile fibers and the resistance of acetate is quite low.

Testing conditions were made identical by subjecting the acetate first to the same actual tension (0.68 g./gx.) and then to the same relative tension (13%–14%) as the nylon without changing other factors.* A high cycle number (6,199) was obtained for nylon, while the cycle numbers for acetate in both cases were very low (2 and 19). This indicates that the testing conditions were not severe enough for nylon (since an unduly long time, approximately 1 hr., was necessary for a single test), while, on the other hand, they were too severe for acetate, since rupture occurred in a few seconds. Textile fibers with such great differences in abrasive behavior must be tested under different testing conditions if the tests are to be performed in a reasonable length of time. A way must be found, of course, which permits valid comparison of cycle numbers obtained at different severities for the evaluation of different fibers.

The severity of attrition was varied by changing the pressure and tension exerted on the yarns, and also by changing the bundle size (the number of strands in the yarn bundle).

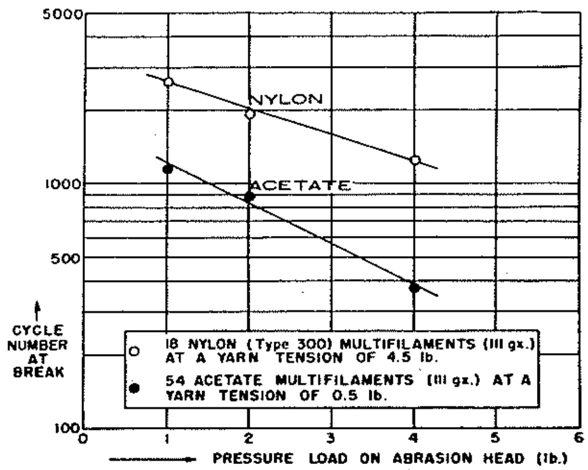

FIG. 8. *Influence of yarn pressure on cycle numbers.*

Tests at varied pressures were performed on yarn bundles of nylon and acetate multifilaments. Figure 8 shows that although a higher pressure decreases the cycle numbers at break, an increase of pressure (within the practicable limits of the tester) does not markedly influence the severity of the test. This can be accomplished better by increasing the tension. Tests at varied yarn tensions were made on yarn bundles of a spun nylon yarn and of viscose and acetate multifilaments † of different total grex (containing different numbers). An essential decrease of the cycle numbers is observable in Figure 9 at higher tensions, indicating the considerably increased severity of the abrasion. A similar decrease of cycle numbers at increasing tensions was previously ob-

* The relative tension of the acetate bundle was diminished by increasing the number of yarn strands (from 27 to 108) instead of reducing the tensioning load, which remained constant. This was necessarily connected with a much lower actual tension (0.17 g./gx.) for acetate than for nylon (0.68 g./gx.).

† The characteristics of these yarns are listed in Table IV (nos. 5, 8, and 20).

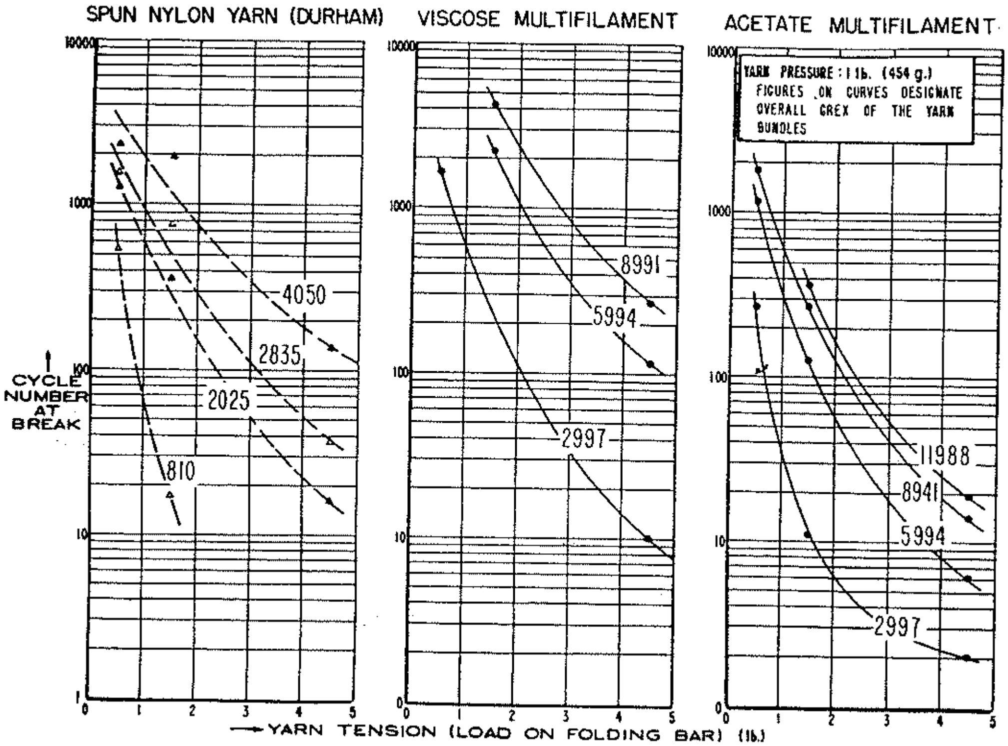

FIG. 9. *Influence of yarn tension on cycle numbers.*

served by Matthes and Keworkian [8], as shown in Figure 10. In these tests, two loops of a staple viscose yarn of varied coarseness were abraded against each other using the T. H. Aachen yarn abrasion tester. When a larger number of yarn strands or a coarser yarn is abraded, more abrasive work is required for rupture and consequently higher cycle numbers appear for all the fibers demonstrated in Figures 9 and 10.

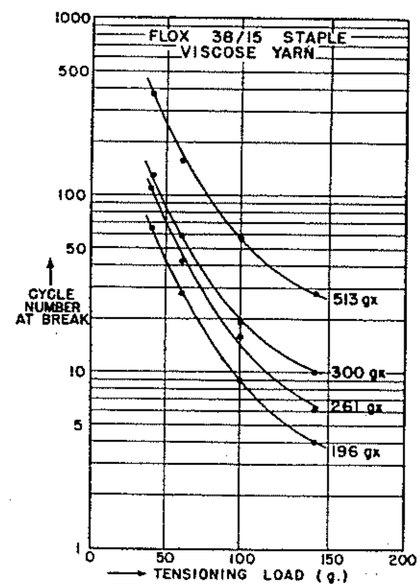

FIG. 10. *Relationship between yarn tension and cycle numbers (Matthes and Keworkian, 1943).*

The influence of yarn bundle size is better shown in Figure 11 and Table II. In Table II, the abrasion of nylon multifilaments and of two nylon staple yarns (60/1 Aberfoyle and 30/2 Durham) * is demonstrated in three sections representing three different severities of attrition. The severity was diminished here by reducing the tensioning load without changing the pressure. The curves of Figure 11 show that the cycle numbers increase very rapidly by increasing the yarn bundle size. The exponential relationship fully justifies the evaluation procedure suggested by Schiefer and Werntz [11]—namely, comparison of logarithms of cycle numbers instead of numerical values of cycle numbers in laboratory abrasion tests. The evaluation of these authors is more realistic than comparison of "sky-rocketing" cycle numbers so far as the substance destroyed is taken into consideration. The curves shown in Figure 11 also provide the cycle numbers at break for any required bundle size, as well as the bundle size which fails in any cycle numbers within the limits of tests performed. A graphical extra-

* The characteristics of these yarns are listed in Table IV (nos. 1, 3, and 5).

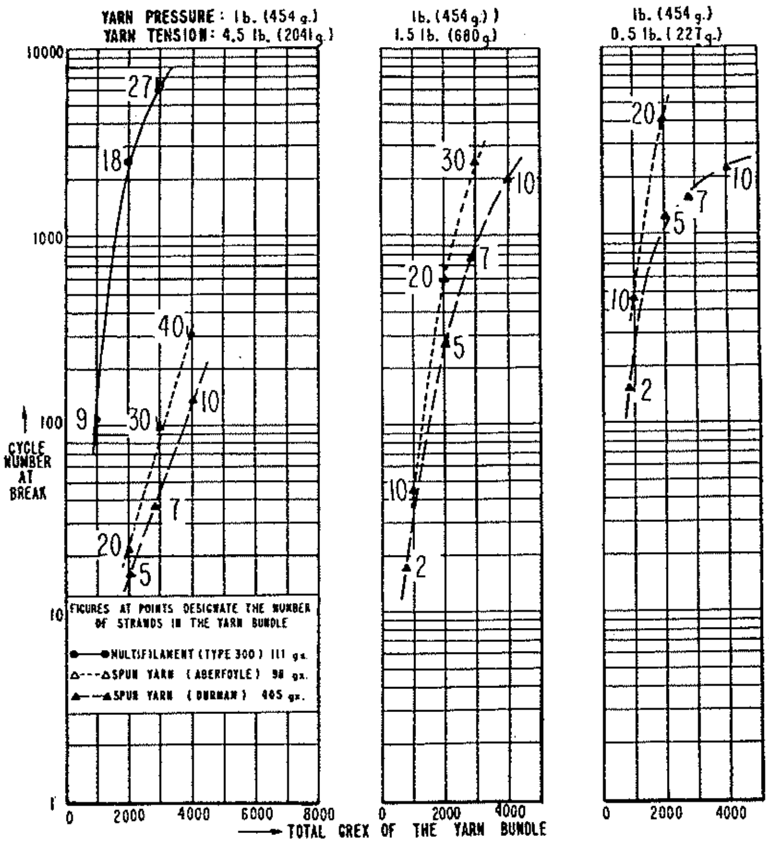

FIG. 11. *Influence of bundle size (grex) of nylon yarns on cycle numbers.*

TABLE II. FLEX ABRASION TESTS OF NYLON YARNS AT VARIOUS TENSIONING LOADS *

Yarn bundle: Number of yarn strands	Yarn bundle: Total grex	Tensioning load, 4.5 lbs. (2,041 g.) Tension: Actual (g./gx.)	Tensioning load, 4.5 lbs. (2,041 g.) Tension: Relative (% of tenacity at break)	Tensioning load, 4.5 lbs. (2,041 g.) Cycle numbers at break	Tensioning load, 1.5 lbs. (680 g.) Tension: Actual (g./gx.)	Tensioning load, 1.5 lbs. (680 g.) Tension: Relative (% of tenacity at break)	Tensioning load, 1.5 lbs. (680 g.) Cycle numbers at break	Tensioning load, 0.5 lbs. (227 g.) Tension: Actual (g./gx.)	Tensioning load, 0.5 lbs. (227 g.) Tension: Relative (% of tenacity at break)	Tensioning load, 0.5 lbs. (227 g.) Cycle numbers at break
				Multifilament (Type 300) No. 1 †						
9	999	2.04	37	107						
18	1,998	1.02	19	2,500						
27	2,997	0.68	13	6,199						
				60/1 Staple Yarn (Aberfoyle) No. 3 †						
10	980				0.70	32	45	0.23	10	462
20	1,960	1.05	47	22	0.35	16	597	0.12	5	4,131
30	2,940	0.70	32	98	0.23	10	2,458			
40	3,920	0.52	24	310						
				30/2 Staple Yarn (Durham) No. 5 †						
2	810				0.84	35	17	0.28	12	154
5	2,025	1.01	42	16	0.34	14	268	0.11	5	1,238
7	2,835	0.72	30	37	0.24	10	769	0.08	3	1,540
10	4,050	0.51	21	136	0.17	7	1,979	0.06	2	2,246

* Test conditions: Yarn pressure, 1 lb. (454 g.): other conditions the same as in Table I, except when otherwise specified.
† Table IV and Figure 16.

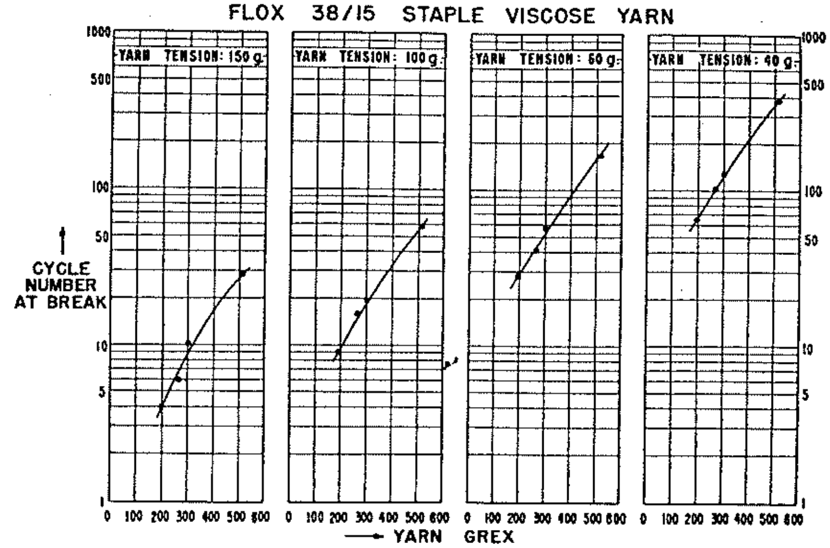

FIG. 12. *Relationship between yarn size and cycle numbers (Matthes and Keworkian, 1943).*

polation on such curves is used in a new testing technique described later (see p. 218) in order to obtain the fiber grex abraded in a constant number of cycles selected as the comparison level for the abrasion of various fibers. It can be seen from the curves of Figure 11 that an approximately linear relationship exists between the logarithms of cycle numbers and numerical values of yarn grex for points sufficiently close to each other on the curves. These observations are in full agreement with the discussed results of Matthes and Keworkian [8] obtained on different sizes (196–513 grex) of a viscose staple yarn tested at varied severities of attrition, as demonstrated in Figure 12.

Numerical data of the curves demonstrated in the three sections of Figure 11 are shown in Table II, where yarn tension appears as tensioning load (in lbs. and g.), as actual tension (in g./gx. tenacity values), and as relative tension (in % of tenacity at break). At each severity a progressively increased number of yarns was abraded corresponding to yarn bundle sizes from roughly 1,000 to 4,000 total grex.* Since the tensioning load remained unchanged in each section, the increase of the bundle size (total grex) necessarily reduced the actual and relative tensions exerted to the yarn bundle, thus also diminishing the severity of the tests. In view of this fact, the cycle numbers at break increased considerably with increasing grex of the yarn bundle.

In contrast to the tensioning load, which remains constant during the abrasion, the actual and relative tensions listed in Table II apply only to the beginning of the test. They increase with the attrition of the yarn bundle, first slowly and then rapidly until the tenacity at break is reached at the end of the test. Rupture occurs, therefore, in these abrasion tests partly as a result of an excessive tension applied to the yarns.

Comparison of Cycle Numbers

By changing the pressure and tension exerted and the number of yarn strands in the yarn bundle, it is possible to arrive at conditions under which all commercial textile fibers can be abraded using the above-described technique in a reasonable number of cycles (between 100 and 1,000) and length of time (1–8 min.) for each test.

A quantitative comparison of different fibers is possible from a series of such tests if conducted under identical testing conditions. Figure 11, for example, shows that nylon multifilaments which could be tested only at the highest severity have a much greater abrasion-resistance than the two staple yarns. The 60/1 Aberfoyle staple yarn appears slightly more resistant than the 30/2 Durham staple yarn at all three tensions. The Aberfoyle yarn is a single yarn; it is finer, has finer staple, is weaker, and is less extensible but more elastic than the Durham

* Nylon multifilament bundles could not be abraded at 1.5 lbs. and 0.5 lb. tensioning loads without increasing excessively the cycle numbers at break and the time necessary for each test.

yarn. The characteristics of these two yarns are as follows:

	30/1 Aberfoyle	60/2 Durham
Staple fineness	1.7 gx.	3.3 gx.
Staple length	1.5 in. (3.8 cm.)	1.5 in. (3.8 cm.)
Yarn fineness	98 gx.	405 gx.
Twist multiplier	3.24	3.29/2.58
Breaking tenacity	2.21 g./gx.	2.40 g./gx.
Extensibility	22.0%	31.7%
Recoverable elongation (at the breaking point)	79%	66%
Elastic energy (of total)	68%	52%

It will be shown later that high elasticity of yarns is critical for good resistance to abrasion. Conducting such abrasion tests as shown for these nylon yarns is, of course, time-consuming. Moreover, a quantitative comparison of fibers tested under different severities is not possible. Even slight changes in the testing conditions affect the cycle numbers at break considerably and in a complex way which is certainly not uniform for all textile fibers. Therefore, it is difficult to transform cycle numbers observed under different testing conditions into comparable values.

Testing Procedure Used to Obtain Abrasion Damage

A new testing and evaluation method has been used in this study in order to measure quantitatively the resistance to abrasion of various textile fibers with great differences in abrasive behavior. In these tests, the destructive action (cycle number) is kept constant, and the abrasion damage is measured. This is expressed by the grex or yarn fineness (weight per unit length) destroyed. The abrasion damage obtained for various fibers is then correlated to that suffered by nylon multifilaments, and is denoted as "relative abrasion damage." The relative abrasive damage is, therefore, a dimensionless number which indicates how much more grex of a fiber is abraded at failure than of a highly resistant nylon multifilament exposed to the same conditions. This comparison eliminates some inadequacies of the testing procedure carried out under conditions that are necessarily arbitrary.

It was found suitable to compare the abrasive damages of commercial fibers (under the above-described testing conditions) after 120 cycles, which require only 1 min. for a single abrasion test. A low cycle number was selected for comparison merely on the grounds of economy. Comparison at lower cycle numbers than 120 can hardly be recommended, but there is no objection to using higher numbers, such as 240 or even 1,200. Tests at higher cycle numbers would be appropriate for less severe abrasive actions —*e.g.*, if a folding bar with round edges, or lower pressures and tensions, or fewer cycle numbers per minute are used. Tests at higher cycle numbers would also be necessary if the rate of abrasion were to be investigated. Any change in the comparison level and in the severity of tests would, of course, affect the abrasion results obtained, and in some cases it might even affect the relative ranking of fibers with similar resistance to abrasion.

It would be difficult to find directly the fiber grex that fails in 120 cycles. This value can be obtained in a simple way, however, if yarn bundles containing varied numbers of yarns are tested which require cycle numbers close to 120 cycles for rupture. The fiber grex abraded in 120 cycles can then be obtained graphically from these tests assuming a linear relationship between the logarithms of cycle numbers and numerical values for the total grex of the yarn bundle which fails. This assumption is valid for points which lie sufficiently close to each other on the curve representing the relationship between cycle numbers and grex abraded (as shown in Figures 11 and 12), and there can be no objection to such an extrapolation if carried out within reasonable limits.

In the testing procedure, yarn bundles in two or even three different sizes were abraded for each material, at least one of them requiring less, and another more, than 120 cycles for rupture. The closer the cycle numbers approximate 120 cycles, the less is the possibility of misrepresentation due to the extrapolation and to other distorting factors. Therefore, only yarn bundles requiring more than 20 and less than 600 cycles were tested and evaluated. It is not difficult to estimate the proper number of yarn strands to be tested in the yarn bundle if the destructive action of the tester and the fineness, structure, and abrasive behavior of the yarn are known approximately. Otherwise, the suitable bundle size must be found by trial and error. This can be carried out easily in a surprisingly short time. The testing of five identical bundles to obtain an average is accomplished within a few minutes, and represents a considerable saving of time if compared to conventional abrasion tests. Although the abrasion of two or even three bundle sizes increases the time necessary for performing a complete set of tests, this additional time is still moderate, and is unavoidable if reliable results are expected.

It is obvious that abrasion tests should be performed under identical conditions in order to obtain directly comparable results. Any deviations from an accepted standard procedure affect the results, and sometimes in such a way that it cannot be accounted for correctly. Unfortunately, testing conditions could not be kept identical in any respect for all commercially available yarns. They were abraded, however, under as similar conditions as feasible. Multifilaments and staple yarns with fairly similar form factors and in yarn sizes between 98 and 456 grex * were tested. The number of strands in the yarn bundle was never less than 8 or more than 80, and the over-all grex of the yarn bundle was in all but a very few cases between 1,000 and 12,000 grex. These precautions were necessary to avoid marked distortions of results.

Nylon multifilaments (which served as the basis in correlating the abrasion damages) had to be tested under a rather severe destructive action using 4 lbs. (1,814 g.) pressure and tension. Most yarns could not be abraded under the same conditions within the above limitations. Therefore, the severity of the abrasion was diminished by decreasing the yarn pressure and tension simultaneously to 2 lbs., 1 lb., and 0.5 lb. without changing other parameters. This measure made it possible to test even fibers with very low inherent abrasion-resistance within the above restrictions. Damages observed at these milder testing conditions were then transformed by calculation to make them comparable with the damage of nylon obtained at the highest severity. Viscose multifilament was selected as a reference fiber to detect quantitatively the decreased attrition brought about by the diminished pressure and tension. The medium abrasive behavior of viscose multifilament makes it convenient for testing at all four severities (4 lbs., 2 lbs., 1 lb., and 0.5 lb. pressure and tension) without deviating from the above requirements.

Details of the testing and evaluation procedure are demonstrated in Table III and Figure 13 for nylon, viscose, and acetate multifilaments of 111 gx. (nos. 1, 8, and 20, respectively, Table IV). Yarn bundles consisting of 8, 10, and 14 nylon yarn strands were abraded at 4 lbs. yarn pressure and tension. From these tests, 1,120 grex was obtained by extrapolation † as the fineness of nylon abraded in 120 cycles. (In the lower left part of Figure 13, 1,120-grex value appears at the intersection of the vertical line for 120 cycles, with the slightly inclined line representing the relationship between the grex abraded and the cycle numbers at break.) Much coarser yarn bundles of viscose (50 and 60 multifilaments) had to be tested at the same severity in order to obtain cycle numbers at break close to 120. An extrapolation gave 6,200 grex as abrasion damage of viscose in 120 cycles. The ratio between the grex values of viscose and nylon (6,200 and 1,120) is 5.53 and represents the relative abrasion damage of viscose compared to nylon. This figure indicates that 5.53 times more (by weight or grex) viscose was abraded than nylon in the abrasion tests performed.

The acetate multifilaments could not be tested under such severe conditions without greatly increasing the number of yarn strands. They were abraded under markedly milder conditions, using only 0.5 lb. pressure and tension. Acetate yarn bundles consisting of 20, 30, and 40 strands were abraded, and 2,750 grex abrasion damage was obtained in 120 cycles. Viscose was also tested as a reference fiber under these milder conditions using 8, 10, 12, and 15 yarn strands. The abrasion damage of viscose in 120 cycles was now only 1,100 grex.‡ A comparison of the abrasion damages of acetate and viscose (2,750 and 1,100 grex) shows that 2.50 times more acetate than viscose was abraded at the low severity of 0.5 lb. pressure and tension. Multiplication of this ratio (2.50) by the relative abrasion damage of viscose obtained at the high severity (5.53) gives the relative abrasion damage of acetate as 13.83 times higher than that of nylon at the high severity of 4 lbs. yarn pressure and tension. This value indicates that the same destructive action abrades acetate 13.8 times

* Although yarn size is generally expressed in denier for multifilaments and by the yarn number in cotton or worsted counts for staple yarns, the universal grex yarn numbering system was adopted to designate the yarn size. This permits the direct comparison of yarn finenesses for all the materials tested.

† In the graphic extrapolation, preference was given to cycle numbers close to 120. The cycle numbers for 10 yarn strands in Table III were obtained on different days, and they indicate the rather low reproducibility observed. Figure 13 shows, however, that the grex value of fiber damage (at the comparison level of 120 cycles) is only slightly affected by such great variations.

‡ The destruction of 1,100-grex viscose is, of course, much lower here than 6,200 grex previously according to the appreciably milder abrasive action of these tests.

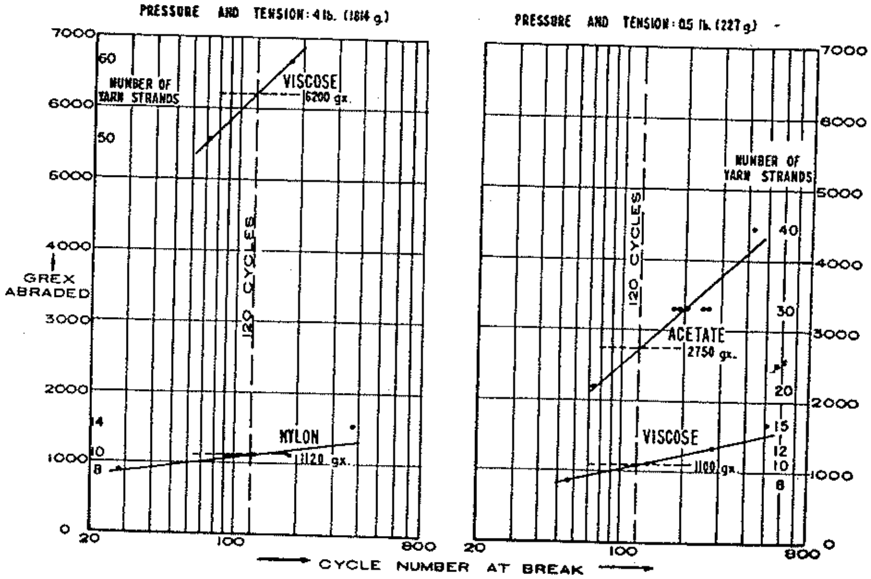

Fig. 13. *Demonstration of the testing and evaluation procedure.*

TABLE III. Procedure for Testing the Abrasion Damage of Nylon, Viscose, and Acetate Multifilaments *

Yarn bundle		Yarn tension and pressure, 4 lbs. (1,814 g.)			Yarn bundle		Yarn tension and pressure, 0.5 lb. (227 g.)		
Number of yarn strands	Total grex	Actual tension (g./gx.)	Relative tension (% of tenacity at break)	Cycle numbers at break	Number of yarn strands	Total grex	Actual tension (g./gx.)	Relative tension (% of tenacity at break)	Cycle numbers at break
				Nylon Multifilament					
8	888	2.05	38	28					
10	1,110	1.63	30	96					
10	1,110	1.63	30	123					
10	1,110	1.63	30	186					
14	1,554	1.17	21	381					
	1,120	1.63	30	120					
				Viscose Multifilament					
50	5,550	0.33	19	72	8	888	0.26	15	56
60	6,660	0.27	16	179	10	1,110	0.20	11	136
					12	1,332	0.17	10	276
					15	1,665	0.14	8	506
	6,200	0.29	17	120		1,110	0.21	12	120
				Acetate Multifilament					
					20	2,220	0.10	8	73
					20	2,220	0.10	8	75
					30	3,330	0.07	5	177
					30	3,330	0.07	5	189
					30	3,330	0.07	5	207
					30	3,330	0.07	5	245
					30	3,330	0.07	5	262
					40	4,440	0.05	4	424
						2,750	0.08	6	120

* Test conditions: the same as in Table I, except when otherwise specified. Demonstrated in Figure 13. Characteristics of the yarns tested are listed in Table IV under nos. 1, 8, and 20.

as much as nylon. The calculated value of the relative abrasion damage of acetate is, of course, an approximation because the translation of a damage under mild conditions into one at high severity is not necessarily exactly the same for acetate as for viscose. It is known that abrasion proceeds at different rates in fibers. It can be assumed, however, that the behavior of viscose at varied severities represents with fair approximation an average progression of abrasion from which that of the other fibers tested might not deviate too significantly.

The tensions applied to the yarn bundles in the tests and at the extrapolated comparison level of 120 cycles are shown in more detail in Table III. The actual and relative tensions decrease markedly in each series of tests with increasing number of yarn strands in the bundle as an obvious consequence of increasing the bundle size (total grex) at a constant tensioning load. Besides this, the actual and relative yarn tensions at the comparison level diminish considerably from nylon to viscose to acetate according to their decreasing abrasion-resistance.* No doubt the decreased tensions affect the abrasion damages observed, since a lower yarn tension corresponds to less severe attrition. Therefore, a lower abrasion damage is obtained in these tests for fibers with low resistance than for highly resistant fibers. The tests performed favor, in a sense, fibers with low resistance and they penalize highly resistant fibers. This causes some distortion of the abrasion damages observed, which is unavoidable for tests carried out at constant pressure and tensioning loads. This distortion is not serious, however, so long as one realizes its origin and consequences. Without this distortion, the abrasion damage of poorly resistant fibers would become even higher than obtained in this study, and the "spectrum" of abrasion damage (as demonstrated in Figures 14 and 16) would appear extended in the direction of higher abrasion damage.

Abrasion tests could be performed at equal actual pressure and tension values (g./gx.), but this would require a marked change in the pressure and tensioning load for each different bundle size. They could also be performed at a fixed percentage of the breaking tenacity (*i.e.*, at identical relative tensions), but this would mean that testing fibers with different breaking tenacities and bundles of varied fineness would differ in the actual tensions (g./gx.) and in

* The significance of actual and relative yarn tensions is discussed later (see p. 225).

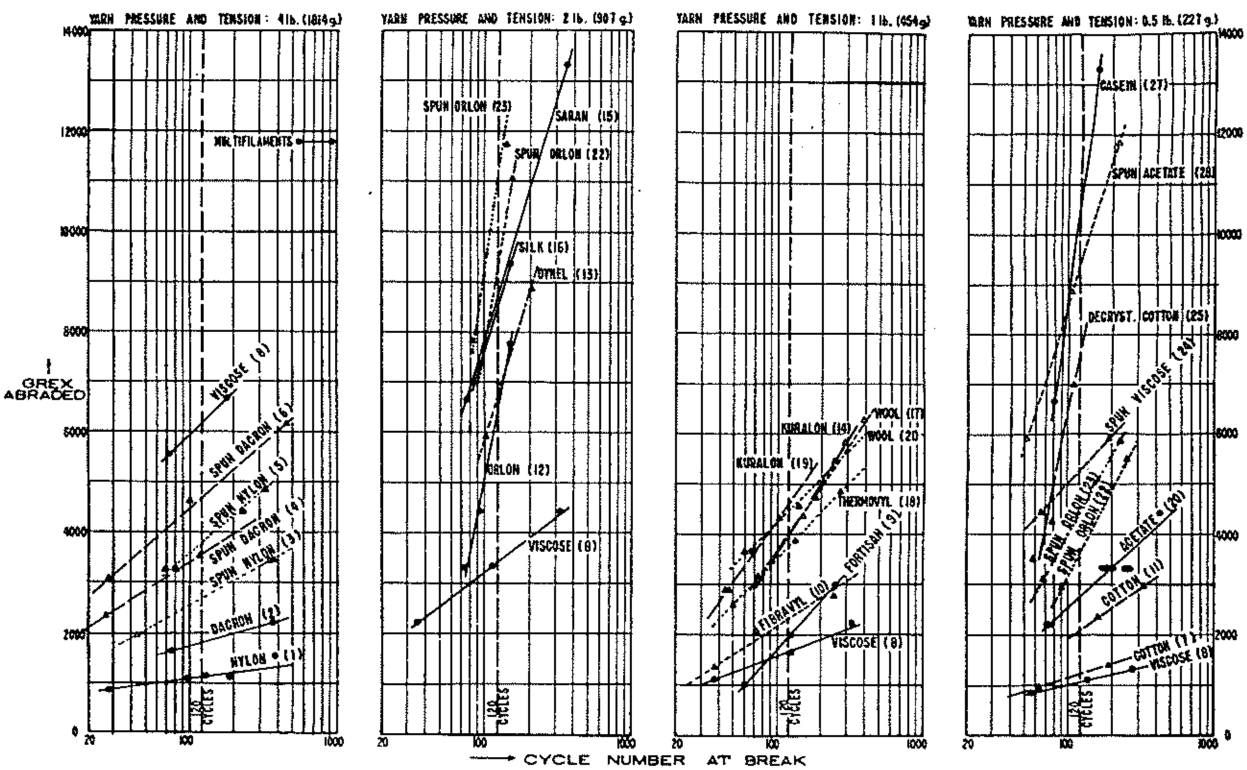

FIG. 14. *Flex abrasion tests performed on different textile materials.*

TABLE IV. ABRASION DAMAGE

1	2	3	4	5	6	7	8	9
	Characteristic				Abrasion damage observed (grex abraded in 120 cycles) Tested at a			
Designation	Yarn type	Yarn fineness (gx.)	Tenacity at break (g./gx.)	Elongation at break (%)	4 lbs. (1,814 g.)	2 lbs. (907 g.)	1 lb. (454 g.)	0.5 lb. (227 g.)
1. Nylon Type 300, 100/40/2.5	multifilament	111	5.45	21.4	1,120†			
2. Dacron polyester fiber 100/40	multifilament	111	5.28	18.1	1,800†			
3. Nylon 60/1 (Aberfoyle)	staple yarn	98	2.21	22.0	2,650†			
4. Dacron polyester fiber 20/1 (Dixie)	staple yarn	295	2.42	38.0	3,550†	1,850		
5. Nylon 30/2 (Durham)	staple yarn	405	2.40	31.7	3,750†			
6. Dacron polyester fiber 60/2 (Phaar)	staple yarn	309	2.78	39.7	4,700†			
7. Cotton 50/1	staple yarn	118	1.88	5.7		2,950		1,200†
8. Viscose 100/40	multifilament	111	1.75	15.7	6,200†	3,400†	1,700†	1,100†
9. Fortisan 90/120/3	multifilament	100	6.95	5.6			1,950†	1,150
10. Fibravyl 75/1 (Rhodia)	staple yarn	138	1.41	18.9			2,300†	1,600
11. Cotton 20/1, untreated	staple yarn	297	1.47	9.1		3,600		2,100†
12. Orlon acrylic fiber 100/40	multifilament	111	4.34	15.9	11,500	6,250†		
13. Dynel 20/1	staple yarn	296	1.10	27.5	11,750	6,650†		
14. Kuralon 40/1 (Omni)	staple yarn	146	1.44	20.0			3,900†	2,050
15. Saran 200/12/5	multifilament	222	1.88	15.3		8,600†	3,400	1,950
16. Silk 100/132	multifilament	117	4.02	21.8		8,555†	3,850	1,900
17. Wool 28.4/1	staple yarn	315	0.84	33.2			3,950†	2,480
18. Thermovyl 30/1 (Rhodia)	staple yarn	324	0.29	100.0			3,750†	2,600
19. Kuralon 80/2 (Omni)	staple yarn	144	2.44	11.2			4,600†	2,450
20. Acetate 100/40/2.5	multifilament	111	1.25	24.3			4,250	2,750†
21. Wool 45/2 (WC 3)	staple yarn	456	0.77	34.0		8,300	4,450†	
22. Orlon acrylic fiber 16/1 (Champlain)	staple yarn	369	1.86	13.7		9,300†		3,600†
23. Orlon acrylic fiber 15/1 (Newnan)	staple yarn	391	1.38	24.0		11,250†		4,400†
24. Viscose 20/1	staple yarn	296	1.26	16.2				5,250†
25. Cotton 20/1, decrystallized	staple yarn	350	1.53	17.3				7,600†
26. Acetate 20/1	staple yarn	296	0.88	21.9			13,750	9,350†
27. Casein 300/40	multifilament	333	0.78	41.0				10,500†

* Test conditions: the same as in Table I, except when otherwise specified.
† Demonstrated in Figure 14.
‡ At the (extrapolated) comparison level of 120 cycles.
** Demonstrated in Figure 16.
§ Demonstrated in Figure 17.

the tensioning loads applied. These modifications in the testing and evaluation method also distort test results. They might have some advantages under certain circumstances, but they are not superior to the procedure followed in this study, in which the damage of different materials at a standardized pressure and tensioning load is compared. No testing and evaluation process is conceivable in which viscoelastic fibers with different properties can be abraded under conditions which are identical in every respect. The various fibers, for instance, were not abraded in this study either at a constant actual or at a constant relative strain. Strain was not taken into consideration at all, although the elongation of fibers at the start of the tests (as a result of the tension applied) and also the elongation of yarn bundles during the flexing procedure influence test results. The abrasion of yarn bundles was normalized only with respect to stress (correctly with respect to the tensioning load at the beginning of the test), and this excludes simultaneous normalization with respect to other parameters (*e.g.*, actual or relative tension, strain, recovery, etc.).

It is remarkable that the actual and relative tenof Various Textile Fibers *

10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
								Relative yarn abrasion damage						
Actual yarn tension‡ (g./gx.) yarn pressure and tension of:				Relative yarn tension‡ (% of ultimate)				Tested at a yarn pressure and tension of:						Ratio between multi-filament and staple yarn§
4 lbs.	2 lbs.	1 lb.	0.5 lb.	4 lbs.	2 lbs.	1 lb.	0.5 lb.	4 lbs.	2 lbs.	1 lb.	0.5 lb.	Average**	Range (±%)	
1.63				30				1.00				1.0		
1.01				19				1.61				1.6		
0.68				31				2.37				2.4		1:2.4
0.51	0.49			21	20			3.17	3.02			3.1	3	1:1.9
0.48				20				3.34				3.3		1:3.3
0.39				14				4.20				4.2		1:2.6
	0.31		0.19		17		10		4.80		6.04	5.4	11	
0.29	0.27	0.27	0.21	17	15	15	12	5.53	(5.53)	(5.53)	(5.53)	5.5		
		0.23	0.20			3	3			6.36	5.78	6.1	5	
		0.20	0.14			14	10			7.46	8.06	7.8	4	
	0.25		0.11		17		8		5.84		10.54	8.0	29	
0.16	0.15			6	3			10.28	10.22			10.3	3	
0.15	0.14			14	13			10.48	10.88			10.7	2	
		0.12	0.11			8	7			12.70	10.34	11.5	10	
	0.11	0.13	0.12		6	7	6		14.00	11.06	9.86	11.6	18	
	0.11	0.12	0.12		3	3	3		13.88	12.50	9.58	12.0	18	
		0.12	0.09			14	11			12.80	12.46	12.6	1	
		0.12	0.11			41	39			12.2	13.1	12.7	4	
		0.10	0.09			4	4			15.0	12.3	13.7	9	
		0.11	0.08			9	6			13.8	13.8	13.8	0	
	0.11	0.11			14	13			13.5	14.5		14.0	4	
	0.10		0.06		5		3		15.15		18.2	16.7	9	1:1.6
	0.08		0.05		6		4		18.3		22.2	20.3	10	1:2.0
			0.04				3				26.4	26.4		1:4.8
			0.03				2				38.2	38.2		
		0.03	0.02			3	2			44.6	46.7	45.7	2	1:3.3
			0.02				3				52.6	52.6		

sion values of viscose multifilaments at the comparison level of 120 cycles remain similar in the two series of tests demonstrated in Table III and Figure 13, despite the considerable differences in the pressure and tensioning loads applied. It is obvious that if these tensions at varied severities are substantially different from each other, markedly different abrasion values can be obtained for the same yarn.

Relative Flex Abrasion Damages Observed

The new testing procedure was followed in evaluating 27 yarns (9 multifilaments, 18 staple yarns) representing 14 different textile materials with a wide range of abrasion resistance. Figure 14 and Table IV demonstrate the tests performed under four different severities using yarn pressures and tensions of 4 lbs., 2 lbs., 1 lb., and 0.5 lb. Although data are shown for clarity of presentation in Figure 14 under only one pressure for each yarn (with the exception of viscose multifilament (no. 8) and the two Orlon staple yarns (nos. 22 and 23)), most of the yarns were actually abraded under two and in some cases even three severities, as shown in Table IV. Tests with cycle numbers at break markedly different from 120 were also omitted.

The abrasion behavior of various fibers is demonstrated by more or less inclined straight lines in Figure 14. They are parts of curves showing the relationship between grex abraded and cycle numbers. The steepness of the lines indicates the rate of the attrition. The inclination increases (with some exceptions) * in each section with increasing abrasion damage, and it shows a faster progression of attrition for less resistant yarns. The rate of abrasion is by no means identical for all fibers. Matthes [7] previously found in his yarn abrasion tests that the cycle numbers of glass fibers decreased rapidly with increasing tension, while those of other fibers decreased only moderately. This author demonstrated the abrasion behavior of five fibers (multifilaments of viscose, acetate, and glass fiber, and staple yarns of viscose and wool) by straight lines plotting the logarithm of "specific tension" † against the logarithm of cycle numbers at break (Figure 15*A*).‡ The abrasion lines have different inclinations, and they can be represented by the equation

$$s\sigma^{x} = \text{constant},$$

where s is the cycle number at break, σ a term for tension, and the exponent x a term for flexing. The abrasion lines connect points corresponding to tensile strength (on the ordinate) and to cycle numbers at break of samples without tension (on the abscissa). Obviously, the latter value reflects the resistance to flexing.

If the five abrasion lines close to the area of "convenient abrasion tests" (for cycle numbers between 80 and 800) of Figure 15*A* are replotted with tension values inversed, the pattern shown in Figure 15*B* is obtained. This pattern is remarkably similar to that demonstrated in the four sections of Figure 14, since a decrease in tension is equivalent in these tests to an increase in grex. The inclination of the abrasion lines increases also in Figure 15*B* with decreasing abrasion-resistance of the fibers tested. The abrasion line for glass fibers has an exceptional steepness (like those of Orlon and Fortisan multifilaments in Figure 14), and it reflects the faster progression of attrition in flexing this fiber.

In Figure 14, viscose multifilament as the reference fiber appears in all four sections. The steepness of the viscose lines decreases with diminishing severity of the tests performed, indicating again the slower progression of abrasion under less severe attrition. In the second section of Figure 14, the distance on the vertical line representing 120 cycles (between the intersection of the viscose line and the two fairly parallel lines for spun Orlon acrylic fiber) represents the range of damage which can be conveniently detected at this severity within the previously specified restrictions. This distance appears shortened in the fourth section of Figure 14, and the range of damage which can be tested at this low severity is markedly extended.

Details of these abrasion tests performed are listed in Table IV, where the fibers tested appear in order of increasing inherent abrasion damage observed.

* For example, Orlon acrylic fiber multifilaments (no. 12) in the second section and Fortisan (no. 9) in the third section.

† Specific tension (kg./mm.²) is comparable to actual tension values (g./gx.) used in this study.

‡ Figure 4 of [7].

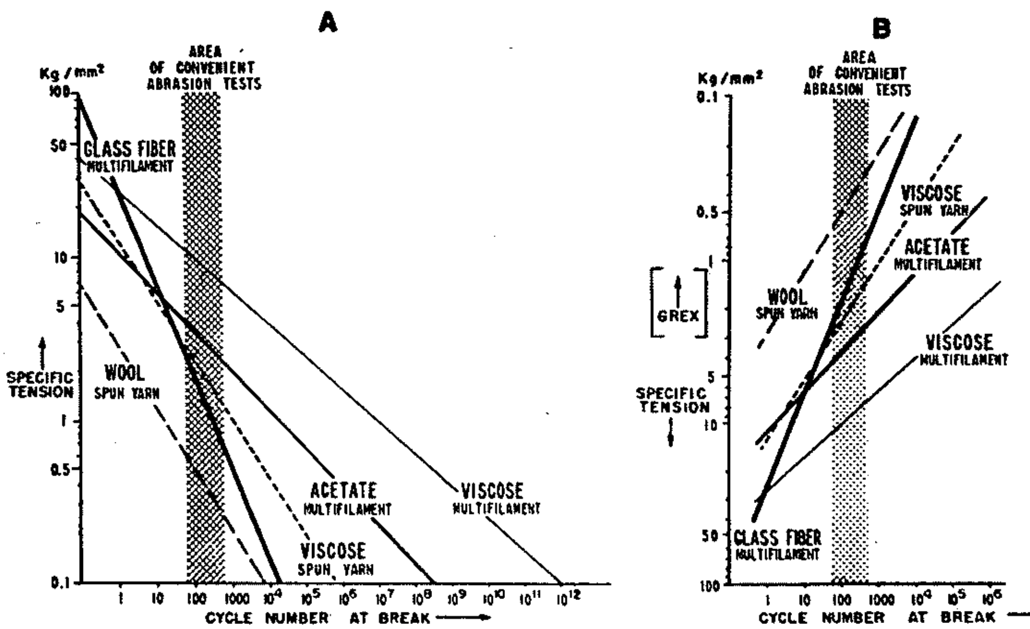

FIG. 15. *Evaluation of yarn abrasion tests performed by Matthes (1947).*

The data in columns 6–9 show clearly that the abrasion damage (the grex abraded in 120 cycles) of all fibers diminishes essentially with decreasing severity. The rate of reduction is roughly identical to that of the tensioning load. The relative abrasion damages obtained at different degrees of severity (columns 18–21), however, do not differ markedly from each other, indicating that the described evaluation method is basically correct. Deviations from the average values (columns 22 and 23) are small in most cases, the greatest being ± 29%. This is remarkable in view of the great variation of cycle numbers observed in individual abrasion tests.

Although actual and relative yarn tensions varied in the tests performed using different bundle sizes, these values are listed in columns 10–17 for that (extrapolated) bundle size which fails in 120 cycles. The data of columns 10–13 show that the actual tension (g./gx.) of the fibers tested decreased markedly with increasing relative abrasion damage of the fiber. The tests performed thus favor fibers with low abrasion-resistance. Nevertheless, the actual tension remains almost unaffected for each fiber * in tests at different severities, despite the considerable differences in the tensioning load applied. A similar, though less consistent, trend is observable when the relative tensions of the fibers tested are compared (columns 14–17).† It is noteworthy that in these tests the ratio between the highest and lowest relative tension (41% and 2%) is markedly less than that for actual tensions (1.63 and 0.02 g./gx.). It is obvious that yarn abrasion should be tested at relatively low tensions, since otherwise the response observed will be that to tension rather than that to abrasion. On the other hand, the tension should not be so low that an excessively long time is necessary for testing, especially when highly resistant fibers are abraded. The actual and relative tension values shown in Table IV were not preselected, but appeared spontaneously as a result of the four tensioning loads applied to the yarn bundles. They represent a fortunate and workable compromise between the conflicting requirements for tension limits.

* Exceptions are nos. 7, 10, and 11.

† Apparently, the values shown for nos. 2, 9, 12, and 16 are too low, while those for nos. 17, 18, and 21 seem to be too high. No explanation can be given for these deviations from the rule.

The average values of relative abrasion damage (column 22, Table IV) are demonstrated graphically in Figure 16 for multifilaments and for staple yarns. A logarithmic scale was selected here to show the small differences in yarns with low abrasion damage (high abrasion resistance) and also the great differences among the textile fibers.

The quantitative data obtained permit the classification of textile fibers into three main groups. The first group (with relative abrasion damage below 5) contains multifilaments and staple yarns of nylon and Dacron polyester fiber corresponding to excellent resistance to abrasion. The majority of textile fibers belong in the second group (relative abrasion damage between 5 and 25) with medium damage. The last group (values above 25) comprises the few materials with high damage or poor resistance to abrasion, and includes staple yarns of viscose, decrystallized cotton, and acetate, and casein multifilament.

Among the new synthetic fibers, only Dacron polyester fiber is comparable to nylon. The damage of Orlon acrylic fiber by abrasion is markedly higher

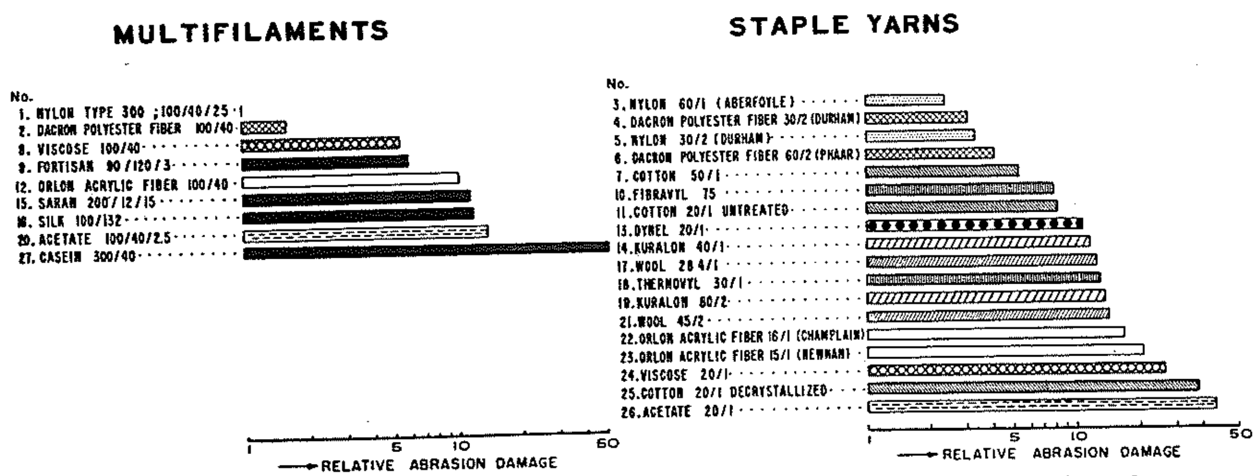

FIG. 16. *Relative abrasion damage of various textile fibers.* (Correction: *No. 4 should read "Dacron polyester fiber 20/1 (Dixie).")*

and not very different from that of viscose. The behavior of the synthetic staple yarns Fibravyl, Dynel, and Kuralon is remarkable. These fibers are considerably more affected by abrasion than staple nylon and Dacron polyester fiber, but appreciably less than staple viscose and acetate. The abrasion damage of cotton yarns is also fairly low, except when the cellulose is present in a decrystallized form [15]. No doubt the form factors and finish of the yarns tested affect the results. Great differences in the form factors of multifilamentous and staple yarns were avoided, and no special finishes were used, so that the results would not be unduly affected thereby. Different staple yarns of the same fiber material * had different form factors and were obtained mostly from different sources, but their relative abrasion damages were very similar as compared to the large differences observed among the various textile materials.

* Staple yarns of 60/1 and 30/2 nylon, 20/1 and 60/2 Dacron polyester fiber, 50/1 and 20/1 cotton, 40/1 and 80/2 Kuralon, 28.4/1 and 45/2 wool, and 16/1 and 15/1 Orlon acrylic fiber.

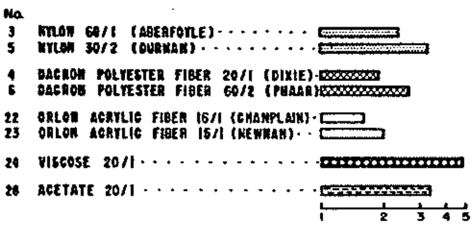

FIG. 17. *Ratio between relative abrasion damage of multifilaments and staple yarns.*

Although the ranking of multifilaments with respect to abrasion damage is essentially the same as that of staple yarns, the relative abrasion damage of spun yarns was always found to be higher than that of multifilaments. The individual staple fibers sticking out from the yarn surface can be easily pulled out or cut through. This causes a loosening and untwisting of the yarns which increases the attrition further if tensional and bending forces act upon the yarn. The ratio between the relative abrasion damage observed for multifilaments and staple yarns (column 24, Table IV) varied from 1:1.6 (for 16/1 Orlon acrylic fiber) to 1:4.8 (for viscose), as demonstrated in Figure 17. A higher abrasion damage of staple yarns has also been observed by other authors. Matthes [7] found a lower resistance to abrasion of viscose, cuprammonium, and acetate staple yarns as compared to multifilaments using the T. H. Aachen yarn abrasion tester. Lower abrasion life was also observed by Hicks and Scroggie [5] for staple yarns than for multifilaments in flat abrasion tests of viscose yarns performed on the Taber tester.

The difference is slight between the relative abrasion damage observed for the two samples of nylon, Dacron polyester fiber, Kuralon, and Orlon acrylic fiber staple yarns, as demonstrated in Figure 16. It is also noteworthy that, with the exception of Kuralon, the less extensible and more elastic sample of each pair suffered the lower damage, despite the fact that considerably lower total energy was necessary for its rupture. In the case of nylon and Dacron

TABLE V. THE ELASTIC BEHAVIOR OF STAPLE YARNS OF NYLON, DACRON POLYESTER FIBER, ORLON ACRYLIC FIBER, AND KURALON

No. in Table IV	Designation	Relative abrasion damage*	Elongation at break (%)	Relative values of elongation components at the breaking point: Immediate elastic recovery	Delayed recovery	Unrecoverable	Total energy of rupture for 1 m. fiber length (g.-cm./gx.)	Relative values of work components (% of total work): Immediately recoverable	Creeping recoverable	Unrecoverable
3	Nylon 60/1 (Aberfoyle)	2.4	22.0	20	59	21	20.2	13	55	32
5	Nylon 30/2 (Durham)	3.3	31.7	13	53	34	35.6	6	46	48
4	Dacron polyester fiber 20/1 (Dixie)	1.6	38.0	10	22	68	46.9	7	17	76
6	Dacron polyester fiber 60/2 (Phaar)	4.2	39.7	11	20	69	57.1	8	11	81
14	Kuralon 40/1 (Omni)	11.5	20.0	11	39	50	15.5	9	33	58
19	Kuralon 80/2 (Omni)	13.7	11.2	18	54	28	12.8	12	54	34
22	Orlon acrylic fiber 16/1 (Champlain)	16.7	13.7	19	55	26	14.8	12	59	29
23	Orlon acrylic fiber 15/1 (Newnan)	20.3	24.0	16	34	50	22.9	10	31	59

* See column 22, Table IV, and Figure 16.

polyester fiber, the more resistant sample had also a slightly lower tenacity at break. The superior elasticity of the yarns with lower abrasion damage is revealed by the lower relative values of their unrecoverable elongation component at the breaking point and of their unrecoverable work component (listed in Table V).* The higher flex abrasion damage of the less extensible, markedly stronger, and more elastic 80/2 Kuralon yarn is apparently the result of some "overstretching," which makes the fiber less resistant to forces acting transverse to the fiber length (flexing, shear).

Factors Preventing Abrasion Damage

It will be worthwhile to discuss some factors which prevent abrasion damage. According to Hamburger [4, 6], good abrasion-resistance (low damage) depends more on high energy necessary for rupture than on high tenacity at break. It is obvious that abrasion will be influenced not so much by the work absorbed in the first deforming process (total energy of rupture) as by the work absorbed during repeated deformations. This work is manifested in the elastic energy or the recoverable portion of the total energy (the sum of immediately recoverable and creeping recoverable work components). It is also revealed in the work absorption of fibers after repeated deformations (mechanical conditioning). It is obvious that the energies necessary for breakdown in compression, bending, and shear are as important for the evaluation of flex abrasion as the energy necessary for rupture in tension (when deforming forces act parallel to the fiber length). Unfortunately, the former energies are unknown, but their relative ranking for textile fibers is presumably not greatly different from that in tension. Therefore, the elastic energies in tension (as revealed by the areas under the recoverable elongation of the stress-strain curves) permit at least a qualitative interpretation of abrasive damage in most cases.

Drawn nylon multifilaments require the highest energy for rupture among the known commercial textile fibers because of their high tenacity and high extensibility. The predominant part of this total energy is recoverable due to the high elasticity of drawn nylon. The tensile properties of high-tenacity nylon multifilaments remain almost unaffected by mechanical conditioning [14], and, consequently, the work absorption does not diminish markedly if the deformation is repeated. This prevents the destruction of nylon by frequently repeated flex abrasion, and is responsible for its extraordinarily low abrasion damage. On the other hand, staple nylon yarns usually have lower tenacity and elasticity but higher extensibility than multifilaments. They are, of course, markedly affected by mechanical conditioning, which diminishes their energy necessary for rupture after the first deformation. An additional disadvantageous factor here is the looser yarn structure. The abrasive damage of staple nylon yarn is, therefore, higher than that of nylon multifilaments.

Wool yarns require a relatively high work for rupture, despite their rather low tenacity. Their elastic behavior is also excellent, and is comparable to that of nylon. No appreciable loss in work absorption occurs in the repeated tensioning of wool. This explains the comparatively low abrasion damage observed for wool yarns. The properties favoring low damage by abrasion are not present to such a degree in casein. Therefore, casein suffers a much higher destruction than wool, despite the similar tenacities and extensibilities of the two fiber types.

Extensibility is also a critical factor in flex abrasion. In frequent flexing of yarns around sharp edges, a considerable elongation at the outside curvature of bent fibers takes place. If this elongation exceeds the extensibility of the fiber, rupture will invariably occur. Although brittle fibers (glass fibers) may have low flex abrasion resistance, too high an extensibility favors flex abrasion damage, especially if the unrecoverable portion of the elongation (permanent set) is considerable. In such cases (*e.g.*, in acetate, decrystallized cotton) the fiber length increases and the fiber cross section diminishes in each cycle. This, in turn, causes stress concentrations and reduced resistance to forces acting perpendicular to the fiber axis (shear), resulting in rupture. It has been shown that in the case of staple yarns of nylon, Dacron polyester fiber, and Orlon acrylic fiber, the less extensible and more elastic samples suffered lower abrasion damage.

The yarn surface, too, is no doubt an important factor for abrasion damage. Finishes may prevent easy detachment of single fibers, particularly in staple yarns, and also may harden and smoothen the yarn surface, thus reducing the friction. On the other

* The actual values of the recoverable energies are not listed in Table V. They were higher for the sample of each pair having the lower abrasion damage, except in the case of Kuralon.

hand, finishes might stiffen yarns and prevent the free mobility and yielding of single fibers in the yarn structure, thus enhancing abrasion damage. All the above factors must be considered in order to understand fully the damage of textile fibers by abrasion.

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